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Decentralized Energy Markets and P2P Contracts: New Opportunities for Automating Energy Exchange

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Abstract

In the current context of energy market transformation – driven by the growing role of renewable energy, the decentralization of generation, and the digitalization of infrastructure – peer-to-peer (P2P) energy contract models are gaining significant importance. These models introduce a new form of energy interaction, fostering local energy communities, increasing market flexibility, and enhancing consumer energy independence. This study aims to analyze the technological, regulatory, and infrastructural factors influencing the implementation of P2P contracts both internationally and in Ukraine, with a focus on decentralized energy systems. The research methodology combines empirical and analytical approaches, including a quantitative comparative analysis of official statistics and an interdisciplinary review of literature. Findings indicate a notable divide between highly digitalized countries and those with transitional economies in terms of P2P adoption. Ukraine, in particular, lags in three critical areas: the proportion of households engaged in peer-to-peer (P2P) trade, the extent of decentralized generation, and the penetration of smart metering. By contrast, successful P2P integration in countries such as Australia, Germany, and the United States is supported by technical readiness, regulatory frameworks, and active community involvement. The value of the study also lies in its policy conclusions regarding the adaptation of international practices to Ukrainian realities of regulation and infrastructure, as well as in the innovative character of the cross-country comparative approach, modified to take into account the unique Ukrainian prescription that identifies specific avenues for enabling digital transformation in the energy sector.

Keywords

Decentralization of the energy market; Energy communities; Digital energy; Renewable energy; Energy democracy; Local energy systems

Introduction

The modern change in the energy sector of the world entails not only the movement out of the centralized pattern of generation but also into a decentralized, digitally controlled market with consumers who are both the manufacturers and prosumers. Climate challenges and the necessity to reduce CO_2 emissions are among the main drivers of this evolution. Equally important are the development of renewable energy sources and the growing demand for energy democracy. In this regard, peer-to-peer contracts are acquiring increased attention as a means of direct interaction between participants in the market for energy without involvement of the traditional intermediaries. The P2P models enable households, businesses, and communities to directly trade energy at the local level, and they provide improved flexibility of the system, transparency of metering, and development of local energy communities. There has been a notable increase in research on P2P energy trading over the last decade. Specifically, a conceptual framework of the P2P energy systems about interconnected communities was created by Tushar *et al.* (2020); automated mechanisms of negotiating energy transactions were introduced by Chakraborty, Baarslag and Kaisers (2020). With a contribution to the technical implementation in the proposal of blockchain architectures to ensure secure exchange, Mu *et al*. (2023) and Laszka *et al*. (2019) helped to figure out a particular issue in the field. Meanwhile, in the context of the most advanced digitalization, most problems still exist, as demonstrated by Fernandes, Christin and Kar (2024) and Saeed, Wen and Afzal (2024), including regulatory fragmentation and restricted access to infrastructure. Notwithstanding the abundance of studies, the corresponding gaps in the scientific literature regard the quantitative cross-nation comparison of the rates of the P2P model adoption, specifically, considering the degree of digitalization, the contribution of households, and decentralized generation scale. The Ukrainian context also remains insufficiently studied: the availability of technological solutions is not accompanied by mass consumer involvement in local energy platforms, which necessitates a comprehensive analysis of barriers and prospects. The scientific novelty of the research is the creation of a multi-indicator comparative framework that at the same time quantifies household involvement in P2P trade, the intensity of decentralized generation, and the state of digitalization. In contrast to the prior researches, which have studied these indicators individually, our methodology combines them into one model, which allows identifying more clearly structural gaps between highly digitalized nations and transitional economies. Moreover, the paper brings to the global discourse the contextualization of Ukraine-specific infrastructural and regulatory constraints and, by implication, suggests a different approach to adapting to the P2P models in low-digital-readiness settings.

In this respect, this paper aims to examine the international experience of use of P2P energy contracts, to determine their technologies, regulation, and social success factors, and to evaluate the state and prospects of development of these models in Ukraine. To conduct this part, several objectives were established. These were:

1. To gather and standardize the most important statistical indicators concerning the chosen countries,
2. To conduct a comparative analysis, codify technology solutions, and summarize the instructions on how to adjust the models to the Ukrainian conditions.

It is hypothesized that the adoption of peer-to-peer energy trading models is significantly determined by the combined effect of three structural factors: the level of digitalization, the scale of decentralized generation, and the degree of household involvement. Countries with higher digital readiness and broader distributed generation are expected to demonstrate faster and more effective adoption of P2P models. In contrast, in transitional economies such as Ukraine, regulatory fragmentation and infrastructural constraints moderate this relationship, slowing down consumer engagement despite the availability of technological solutions.

Literature Review

Technical Enablers

The latest studies on the topic of peer-to-peer energy contracts suggest that there is a major transformation in the system of decentralized forms of energy management, which is conditioned by the autonomy of consumers, digitization, and the application of blockchain technologies. To begin with, the possibilities of P2P trading, as an alternative to traditional centralized markets, have been analyzed: the conceptual framework of the formation of energy communities and local markets, based on game simulation, promoting independent pricing and collaboration, is described by Tushar *et al.* (2020) and Chakraborty, Baarslag and Kaisers (2020). The proper performance of such models can also be approved in Vieira and Zhang (2021), where the role of smart contracts in microgrid is explained. The technological enablers of P2P trading include blockchain systems, smart contracts, and IoT devices, which jointly ensure transparency, automation, and efficiency. Mu *et al*. (2023), Boumaiza (2024), Dong *et al*. (2025), and Shen, Ou and Chen (2025) discuss the advantages of decentralized platforms in the field of transparency, security, and low transaction costs. These findings perform comparisons to the findings of Laszka *et al*. (2019), Nasiri (2023), and Sadati, Shivaie and Nazari (2023) studies that outline how such systems can be implemented in an actual setting, considering the limitations of the network as well as the privacy of the users.

Regulatory Frameworks

Where the regulatory dimension and technological dimension coincide, the article explains the problem of legal regulation of P2P models according to the European policy. The European Commission (2016), European Parliament and Council (2016, 2018, 2019), to create the foundation of the development of energy communities by ensuring the right of access to the market, the processing of personal data, also following the provisions of the GDPR, and the right of prosumers. Simultaneously, researchers (Bassey, Rajput and Oyewale, 2024), Rahman *et al*. (2023) also focus on the issues beginning with a legal fragmentation challenge to the digital risks on platforms. The analysis of international experience is done with particular attention. The study by Fernandes, Christin and Kar (2024), Saeed, Wen and Afzal (2024), and Zhou, Wu and Gan (2023) allow comparing the practice of introducing the P2P systems in various countries and arguing that they become successful due to the national policies and the technical infrastructure supporting them. Similarly, Sotnyk *et al*. (2023) survey the literature on the topic of household energy efficiency and make a bibliometric analysis

of trends in the industry, which indicates the increasing importance of the inclusion of renewable energy sources and their integration with decentralized markets.

The research also includes the analysis of successful examples of the dynamic pricing model application (Raja and Grammatico, 2023), energy tokens (Toderean *et al*., 2021), and the incorporation of IoT devices into energy metering and management (Saxena *et al*., 2019). Meanwhile, the implementation of the methods of virtual power plant together with P2P trading is also discussed in Alam, Kaif and Das (2024), and the opportunities of large-scale solutions are noted in the future. In parallel with international developments, the Ukrainian context offers both challenges and opportunities that mirror global trends while revealing country-specific features; thus, the Ukrainian context is no less important. Jiang *et al*. (2019) analyze the use of agricultural waste for energy generation in Ukraine, which could become one of the sources for P2P markets. In turn, Gurieiev *et al*. (2020) examine simulation systems for training power engineers, which is part of the digital transformation of the market. The educational dimension within the framework of continuous learning is revealed in Batsurovska (2023), which focuses on training specialists to work in the digital energy sector. Thus, the Ukrainian case exemplifies how the broader global drivers of P2P trading, technological innovation, regulatory adaptation, and community engagement manifest differently in transitional economies. Complementing the review of studies, attention should be paid to sources that analyze the details of the implementation of decentralized models in the context of security, flexibility, and cost-effectiveness. In particular, Liu and Ai (2024) emphasize the role of blockchain solutions in minimizing transaction costs and optimizing trade processes between households.

The contribution of Ukrainian scientists to the international scientific dialogue deserves special attention. In particular, Sotnyk *et al*. (2023) systematically highlight energy efficiency trends in households, which are directly related to the development of decentralized generation. The work of Gurieiev *et al*. (2020) is of applied importance, demonstrating the importance of digital simulation systems in preparing energy professionals to work in a changing market environment. In her turn, Batsurovska (2023) draws attention to the educational direction of such training, pointing out the necessity of ongoing study in the sphere of energy in the digital world. Jiang *et al*. (2019) supplement the Ukrainian situation by being able to discuss the possibilities of renewable biomass as a source of energy that can be added to the local format of P2P.

The concept of peer-to-peer (P2P) multi-energy trading has become one of the game changers in the decentralized form of energy, where the conventional relationship between producers and consumers of energy is transformed. As it was demonstrated by an extensive review by Tariq and Amin (2025), the technological basis and integration schemes that make P2P multi-energy markets possible rely on the use of blockchain, artificial intelligence, and IoT as their main enablers. The development of the concept of such systems is closely connected with regional innovation processes. Nawrocki and Jonek-Kowalska (2023) focused on the contribution of innovation in energy enterprises in the developing economies and demonstrated that the institutional support and absorptive capacity act as the key determinants of energy innovation.

Socio-Economic Factors

P2P trading is attracting increased socio-economic interest in various aspects. As an example, a discrete choice experiment conducted in Colombia proved consumer preferences to be greatly impacted by trust, price transparency, and environmental awareness (Cárdenas-Álvarez, España and Ortega, 2022). Likewise, Adewole *et al*. (2023) unveiled that household desires to obtain autonomy and reduce costs are also the primary drivers of participation in the decentralized energy systems in Nigeria, despite infrastructural constraints. In terms of methodology, Xia *et al*. (2023) offered a concerted review of optimization methodologies and trading environments in P2P markets with a taxonomy of the corresponding simulation tools and resource allocation models.

All these studies, in a way, create a multidimensional perception of P2P energy trading, which involves the feasibility of P2P energy trading in technological, socio-economic, as well as market optimization aspects; therefore, providing a background on how empirical analyses of P2P energy trading can be contextualized within various regional contexts.

Simultaneously, Raja and Grammatico (2023) offer strategies to equitably divide money among the actors in the energy exchange, which might limit the hazards of inequality in access. Zhou, Wu and Gan (2023), on the other hand, systemize the practical obstacles of P2P models applied in the public energy network, emphasizing technical infrastructure and adaptation of the model to each set of circumstances. Articles concentrating on the technicalities of blockchain solutions applications are supplemented by the applied work on energy tokenization of transactions. Specifically, Toderean *et al*. (2021) described an ERC20 closed-loop token model to guarantee secure and controlled trade in P2P networks, enabling a more managed energy asset treatment. Meanwhile, as proposed by Saxena *et al*. (2019), a pilot project was conducted by the researchers in residential microgrids with the implementation of these digital enablers, which demonstrates the feasibility of this type of system in the real world.

The practical aspect of scaling can be proved by the example of Alam, Kaif and Das (2024) because they developed and tested a laboratory prototype of a virtual power plant as a part of a P2P platform. In the future, it is important for countries with agrarian economies such as Ukraine to consider the potential of local energy sources – as Jiang *et al*. (2019) argue, the use of agricultural residues for electricity production can be integrated into the P2P market. In addition, Blaize Tech's review (Onyshchenko, 2023), although applied, systematizes the technological advantages of blockchain solutions in the energy sector, focusing on scalability, security, and transparency of operations. In general, these works specify ways to implement decentralized energy through digital tools with a high degree of adaptability to local conditions. In addition, the study by Liu and Ai (2024) focuses on the integration of blockchain architecture with demand-side management algorithms, which ensures not only transparency of transactions but also adaptability of tariff setting to load fluctuations in microgrids. This approach enhances the economic efficiency of P2P models and reduces the risks of imbalance in local power systems. In addition, recent Ukrainian studies emphasize the synergistic role of innovation parks, urban sustainability strategies, and energy-saving technologies in shaping decentralized energy ecosystems and supporting digital energy platforms (Gavkalova *et al*., 2025; Krysovatyy *et al*., 2025; Shlapak *et al*., 2025).

Thus, the reviewed literature shows that there is a growing attention to the technological, regulatory, and socioeconomic aspects of P2P energy development. However, two key issues remain unresolved: first, the lack of universal mechanisms for balancing supply and demand in the face of high variability in renewable energy production; second, the poor synchronization between regulatory initiatives and the level of digital readiness of infrastructure, especially in transition economies. The present study directly addresses these gaps by combining a quantitative cross-country analysis of digital readiness and decentralized generation with a Ukraine-specific examination of regulatory and infrastructural conditions.

Conceptual Framework

In the context of global energy transformations, such as decentralization of generation, the growing role of prosumers (consumers who simultaneously produce energy), and the development of energy communities, theoretical approaches to the functioning of decentralized energy markets have undergone significant changes. At the center of these transformations are peer-to-peer (P2P) models of energy exchange, which offer a radical alternative to traditional centralized energy supply schemes. Among the most important theoretical directions is the notion of energy communities, where households, businesses, and even municipalities are directly allowed to trade extra amounts of electricity that is frequently produced using renewable sources. This conforms to the notions of energy democracy, which picture a fairer energy culture through the division of the energy resources, infrastructural accessibility, and citizen engagement in decision-making processes (Tushar *et al*., 2020).

The third strategy relates to the theory of distributed energy systems, according to which the optimal functioning of energy networks is a combination of decentralized generation facilities into one exchange platform, in which the P2P contract was used as a tool to balance the supply and demand at the local level. In that regard, the significance of cognitive and self-learning systems that can guarantee the self-sustainability of energy dealings is increasing. P2P models have been discussed as one of the solutions to the development of local energy markets because such an approach will help to introduce price signals based on the actual situation on the supply and demand side. These strategies use the economic theory, game theory, and agent-based modeling to forecast how the participants in various trading situations will behave (Chakraborty, Baarslag and Kaisers, 2020).

Speaking of the global trends, one should consider the technological aspect of such strategies, the inclusion of blockchain-based solutions to provide transparency and impossibility of record modification, as well as automatization by using smart contracts and adherence to the principles of cybersecurity and safety of personal data (Mu *et al*., 2023; Laszka *et al*., 2019). This all enhances the confidence of the market players and minimizes the cost of transacting. Key benefits and limitations of peer-to-peer models in decentralized energy markets are summarized in figure 1.

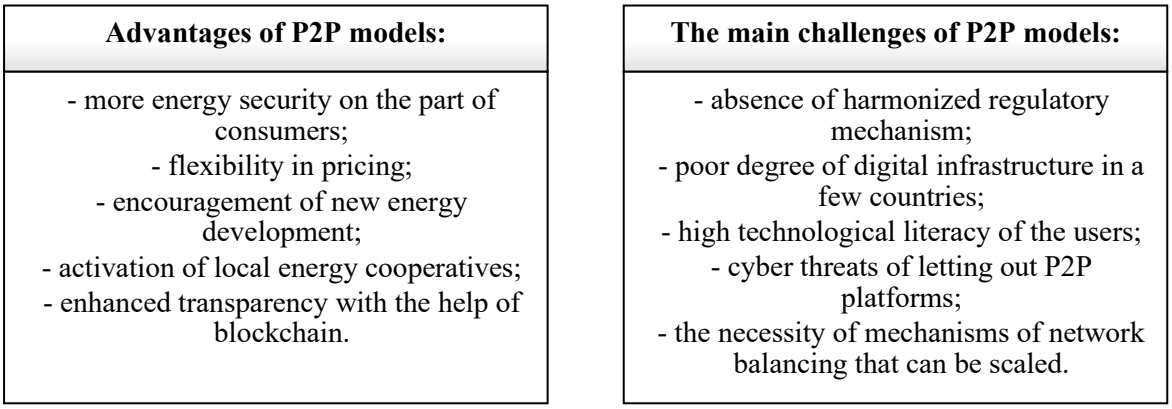
Advantages of P2P models:
- more energy security on the part of consumers;
- flexibility in pricing;
- encouragement of new energy development;
- activation of local energy cooperatives;
- enhanced transparency with the help of blockchain.
The main challenges of P2P models:
- absence of harmonized regulatory mechanism;
- poor degree of digital infrastructure in a few countries;
- high technological literacy of the users;
- cyber threats of letting out P2P platforms;
- the necessity of mechanisms of network balancing that can be scaled.

Figure 1: Advantages and challenges of P2P models [*Source:* Tushar *et al*. (2020), Chakraborty, Baarslag and Kaisers (2020), Mu *et al*. (2023), Laszka *et al*. (2019), Saeed, Wen and Afzal (2024)]

Thus, theoretical approaches to the functioning of decentralized energy markets are increasingly shifting towards models that combine economic efficiency, digital autonomy, and social justice. P2P models are becoming the core of these approaches, and their effective implementation requires the integration of both technological and regulatory and institutional innovations. The modern technology ecosystem of P2P energy platforms is based on a combination of distributed ledgers, smart contracts, digital platforms, IoT devices, and cybersecurity. When put together, they develop an environment that is flexible and such that all parties of energy in the market can consume and even sell energy at transparent and automated conditions. This infrastructure helps to introduce a new level of decentralized energy management and helps to create sustainable communities in energy.

Table 1: Technological tools for implementing P2P contracts in decentralized energy systems

Technology component	*Main function*	*Advantages of implementation*	*Application examples*
Blockchain infrastructure	Ensures consistency and transparency of transaction data	High trust between the parties; decentralized storage of information	TRANSAX (Laszka *et al*., 2019); Hyperledger (Mu *et al*., 2023)
Smart contracts	Automate the fulfilment of contract terms without the participation of third parties	Reduced transaction costs; instant execution of transactions	Ethereum-based P2P platforms (Boumaiza, 2024)
Decentralized exchange platforms	Create digital platforms for energy trading between users	Direct energy exchange; scalability of the system	Power Ledger (Saeed, Wen and Afzal, 2024); Brooklyn Microgrid
Smart meters	Records the volume of energy generation and consumption in real	Accuracy of calculations; support for fair pricing	Used in most pilot P2P projects

Technology component	*Main function*	*Advantages of implementation*	*Application examples*
	time		
Cybersecurity mechanisms	Ensure data confidentiality, integrity, and availability	Preventing unauthorized access; maintaining trust in the platform	Multi-level security protocols (Nasiri, 2023)

Source: Mu *et al*., 2023; Laszka *et al*., 2019; Boumaiza, 2024; Saeed, Wen and Afzal, 2024; Nasiri, 2023

As the energy markets require decentralization, a plethora of nations worldwide have started to introduce peer-to-peer (P2P) energy, where electricity can be exchanged by consumers. The success of such initiatives largely depends on the regulatory environment, technical infrastructure, level of digitalization, and the readiness of local communities to participate in energy self-management.

Methodology

The study was based on an empirical and analytical approach that involved a combination of quantitative analysis of official statistics, verification of cases of implemented P2P initiatives, and an interdisciplinary review of scientific and industry sources. The basis of the empirical analysis was the annual reports of international regulatory organizations – Electric Power Annual 2023 (U.S. Energy Information Administration, 2024), State of the Energy Market 2024 (Australian Energy Regulator, 2024), 2024 Energy Statistics Yearbook (Korea Energy Agency, 2024) and other national reports containing information on: the level of digitalization (in the form of the share of households equipped with smart meters); the share of decentralized generation; the share of households involved in P2P trade.

The key legislative documents in Ukraine regulating the dynamics of the energy market were used: NEURC Resolution No. 307[1] of 14.03.2018 «On Approval of Market Rules» (2018), CMU Resolution No. 499[2] of 05.06.2019 «On Approval of the Procedure for Conducting Electronic Auctions for the Sale of Electricity under Bilateral Contracts and the Procedure for Selecting Organizers of Electronic Auctions for the Sale of Electricity under Bilateral Contracts» (in terms of bilateral contracts) (2019), NEURC Resolution No. 312[3] of 14.03.2018 «On Approval of the Rules of the Retail Electricity Market» (in

[1] Resolution of the National Commission for the Regulation of the Energy and Utilities Sector of Ukraine No. 307 dated 14.03.2018 «On approval of the market rules». https://zakon.rada.gov.ua/laws/show/v0307874-18#Text

[2] Resolution of the Cabinet of Ministers of Ukraine No. 499 dated 05.06.2019 «On approval of the Procedure for conducting electronic auctions for the sale of electricity under bilateral agreements and the Procedure for selecting organizers of electronic auctions for the sale of electricity under bilateral agreements» (in terms of bilateral agreements). https://zakon.rada.gov.ua/laws/show/499-2019-%D0%BF#Text

[3] Resolution of the National Commission for the Regulation of the Energy and Utilities Sector of Ukraine No. 312 dated 14.03.2018 «On approval of the Rules of the retail electricity market» (in terms of a model agreement for the supply of electricity to a consumer). https://zakon.rada.gov.ua/laws/show/v0312874-18#Text

the part of the model contract for the supply of electricity to the consumer) (2018), the Law of Ukraine «On the Electricity Market» No. 2019-VIII[4] (in the part of the legal framework for the functioning of the electricity market, including the conclusion of contracts) (2019).

In order to ensure cross-country comparability of data, the study conducted a procedure for normalizing primary statistical indicators. Taking into account the different scales, units of measurement, and national specifics of data collection, the method of normalization was applied relative to the reference value, i.e., the maximum value of each indicator among all countries included in the sample. This approach makes it possible to bring all values to a single unified scale ranging from 0 to 1, while maintaining the correlation between countries. Formally, this is expressed by the following formula:

$$N = X/max(X) \quad (1).$$

Where: *N* is the normalized value of the indicator;
X is the absolute value of the indicator for a particular country.
max(X) is the maximum value of this indicator among all countries.

This formula was used for three key indicators:
- the share of households involved in peer-to-peer (P2P) trade;
- share of decentralized generation;
- the level of digitalization, defined as the percentage of households equipped with smart meters.

A P2P energy model case was implemented in several countries (Germany, France, the United States, Australia, South Korea, and Ukraine) and evaluated based on the official statistics, such as the U.S. Energy Information Administration (2024), Australian Energy Regulator (2024), and Korea Energy Agency (2024), in empirical-analytical format. To make these indicators comparable, data in 2024 were normalized (three indicators were normalized): (1) the percent of households engaged in P2P trade, (2) the percent of decentralized generation, and (3) the percent of household market digitalization using the percent of households with smart meters. Standardization of values was achieved by converting absolute values to percentages based on the industry reporting standards, and in this way, a fair benchmark of different countries was taken. The statistical survey was reduced and averaged by means of the necessary regional characteristics in the country, in case of a need (e.g., regionally in the country). Then, the data were ready to build graphic models of the development of P2P markets.

All initial absolute values, expressed as percentages, are shown in table 1 of Appendix - A. Normalized values for each country were calculated according to the above formula, as shown in table 2 of Appendix-A. All calculations were made on the basis of data for the most recent available year (2023-2024) obtained from open international sources, in

[4] Law of Ukraine «On the Electricity Market» No. 2019-VIII (regarding the legal framework for the functioning of the electricity market, including the conclusion of contracts). https://zakon.rada.gov.ua/laws/show/2019-19#Text.

particular: U.S. Energy Information Administration, Australian Energy Regulator, Korea Energy Agency, etc. (see the list of sources in Appendix -A).

Results

The introduction of peer-to-peer contracts in the energy sector has become possible due to the rapid development of digital technologies, including blockchain infrastructure, smart contracts, and decentralized exchange platforms. These tools allow for the creation of automated, secure, and transparent mechanisms for interaction between local energy market participants, from individual households to energy communities. Table 1 shows the key components of the technological architecture of P2P energy platforms, as well as their functions, advantages, and examples of implementation. Table 2 presents the comparative dataset compiled by the authors from official reports and statistics (U.S. Energy Information Administration, 2024; Australian Energy Regulator, 2024; Korea Energy Agency, 2024, etc.), systematizing the implementation of P2P initiatives in different countries. Table 2 provides a comparative analysis of P2P cases in the EU, the US, Australia, and South Korea.

Table 2: Comparative analysis of the implementation of P2P energy systems in leading countries

Country/ region	*Name of the initiative/platform*	*Main features of the model*	*Institutional conditions*	*Technical solutions*
Germany (EU)	SonnenCommunity, LichtBlick SchwarmEnergie	Decentralized exchange networks among households	Government support, Feed-in Tariffs	Integration with smart meters, blockchain
France (EU)	ComWatt, Urban Solar Energy	Virtual energy cooperatives	Stimulating energy communities	Platforms for balancing generation and consumption
USA	Brooklyn Microgrid, LO3 Energy	Blockchain-based energy trading between neighbours	Pilot projects under private initiatives	Ethereum smart contracts, IoT
Australia	Power Ledger	National scalability of the P2P model	Support at the state and municipal levels	Energy verification modules, metering tokenization
South Korea	KEPCO P2P Platform	Participation of the state operator in pilot projects	Flexible regulation, institutional testing	Hybrid blockchain infrastructure

Source: Fernandes, Christin and Kar, 2024; Saeed, Wen and Afzal, 2024; Rahman *et al*., 2023; Shen, Ou and Chen, 2025

A brief description of the main business processes of P2P contracts is shown in figure 2.

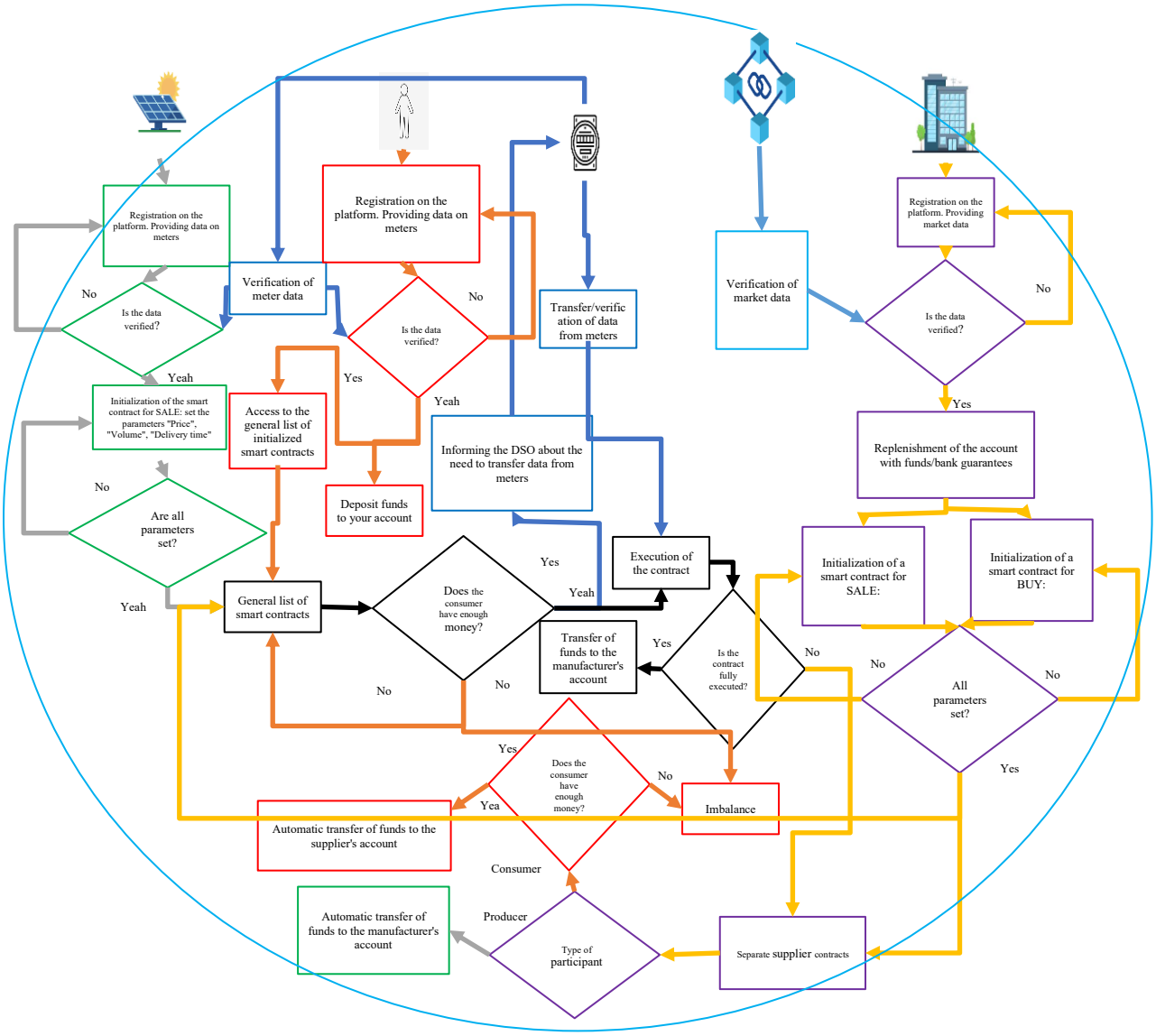

Figure 2: Decentralized market system

The UML diagram of the main business processes of P2P contracts (Figure 2) shows the participants and the main actions in the process of interaction of such participants at different levels:

1) the blockchain platform administers the common platform, as well as verifies the registration of suppliers that can be allowed to work on the platform;
2) producers register on the platform, verify meters with distribution system operators (DSOs), and then initiate contracts that are accepted by consumers. The accepted contracts are then fulfilled by the producers;
3) consumers register on the platform, verify their meters with DSOs, and then accept the desired contracts of producers (if they have funds on their

account), and after the contract is executed, the money is transferred to the producer's account;

4) DSOs verify meters, transmit data on meters, and confirm the fulfilment of the contract;
5) suppliers register on the platform, verify their market data with the blockchain platform, and initialize permanent contracts for the purchase and sale of residual volumes for local balancing purposes.

The process of determining the accepted volumes and prices when concluding P2P contracts, and, as a result, the formation of the relevant transactions for the purchase or sale of electricity, can be divided into the following main components (Figure 3):

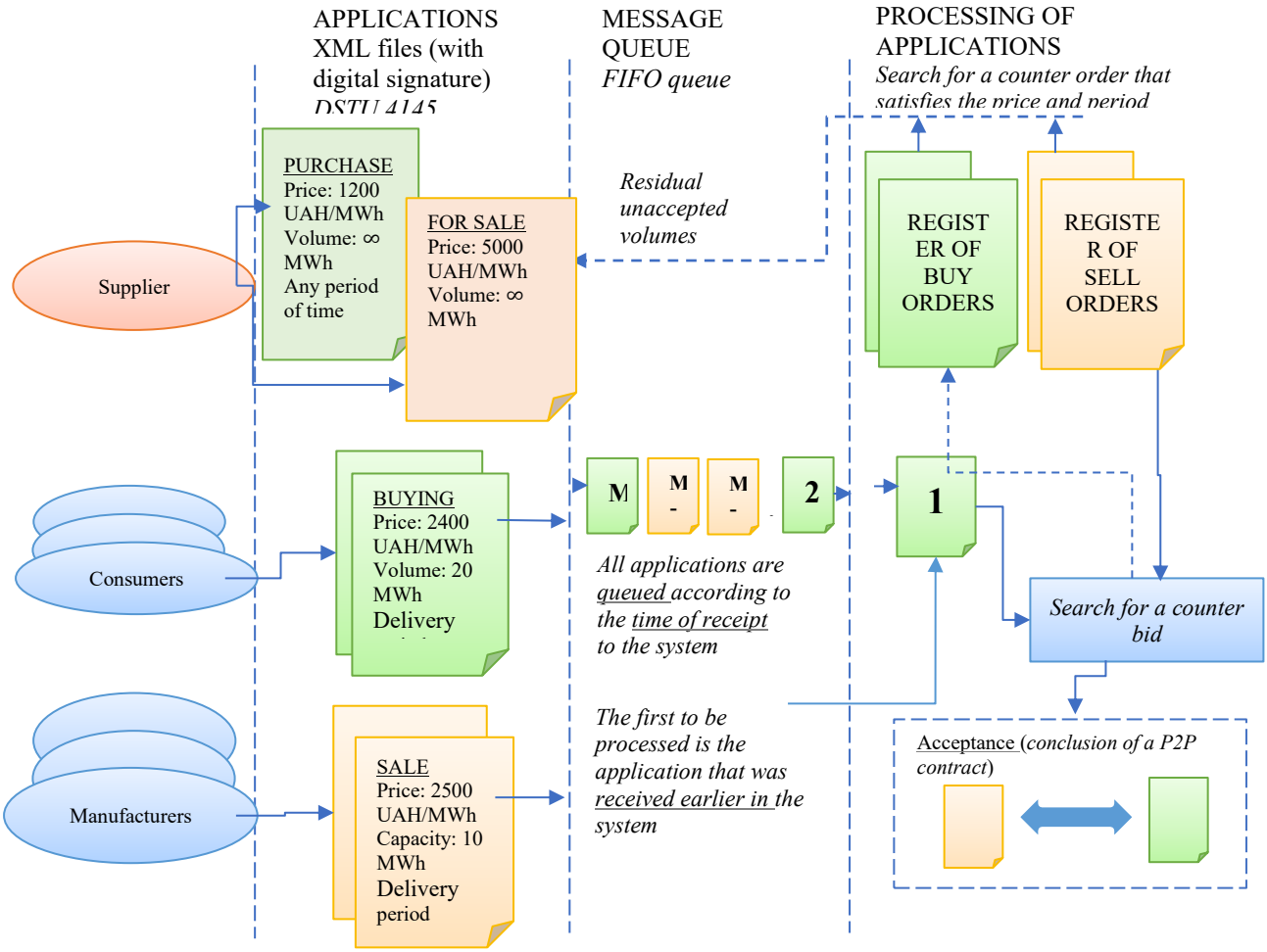

Figure 3: The process of matching bids

1) *Subsystem for receiving bids from bidders*. This subsystem should ensure continuous reception of data on prices, volumes and periods of electricity supply from consumers, producers and suppliers. It should also be noted that this

subsystem should support the mechanism of imposing and verifying a qualified electronic signature (QES) (Polukhin *et al.,* 2024).

2) *Message queue*. This queue operates on the principle of a classic FIFO (First Input First Output) buffer, where, regardless of the intensity (simultaneity) of the receipt of applications to the system, all applications will be processed sequentially one after the other, depending on the time of receipt to the system (Polukhin *et al.,* 2024). As a technical implementation and in order to ensure active updating of the user interface during the bidding process, technologies operating under the AMQP protocol can be used.
3) *Bidding subsystem***.** This subsystem searches for counter bids for their subsequent acceptance and the formation of corresponding transactions. Bids are matched according to the following algorithm (Polukhin and Evdokimov, 2023; Evdokimov and Tsviliy, 2025).
4) *Subsystem for maintaining the register of applications*. This subsystem is designed to store applications that have been received by the system and have not been accepted during their processing. These applications shall be stored until the time during which they can be accepted expires.
5) *Transaction subsystem*. This subsystem is responsible for storing the accepted volumes and prices of matched orders (transactions). It should also be noted that transaction data can be stored in a decentralized database through the use of Blockchain technologies (Polukhin, Evdokimov and Lukashevich, 2025).

An analysis of international experience shows that the most successful examples of P2P energy systems are based on a combination of three factors: support from the state or local government, high technological maturity (primarily due to blockchain architecture, smart contracts, smart meters), and consumer inclusion in market processes. In the EU, the emphasis is on the development of energy communities, in the US – on private initiatives with a focus on innovation, in Australia – on scaling the platform, in South Korea – on involving public infrastructure in experiments with P2P models. These approaches can be adapted in Ukraine, taking into account the national energy context and regulatory specifics (Kovalskyi *et al.,* 2024).

In the context of energy system transformation, a key challenge for many countries is to ensure effective decentralization of the energy market. Peer-to-peer (P2P) energy exchange models are one of the means of enhancing flexibility, transparency, and consumer participation in active energy management in this process. The quantitative review of the implementation of P2P solutions enables us to state the actual extent of evolution of the distribution of such models in various countries, household participation, and the rate of energy markets digitalization. This information will be significant to predict the opportunities for the emergence of Deniz energy systems in Ukraine and substantiate the possibility of changing the regulations.

The analysis of the quantitative indicators in figure 4 allows us to draw a number of significant conclusions about the degree of decentralization of energy markets in the six countries. Australia (19%) is the leader in terms of the share of households participating in P2P trading, 2 percentage points (p.p.) ahead of Germany (17%) and 4 p.p. ahead of the United States (15%). France (12%) and South Korea (14%) have similar values, while Ukraine's figure is only 5%, which is four times less than in Germany and almost

half as much as in South Korea. In terms of the share of decentralized generation, the highest values are observed in Australia (35%), which is 7 percentage points higher than the German level (28%) and more than three times higher than the Ukrainian level (9%). The United States (25%) and France (22%) demonstrate average values, and South Korea, 20%. Thus, the gap between the highest (Australia) and the lowest (Ukraine) is 26 percentage points, which indicates that Ukraine is lagging far behind in the implementation of small-scale generation facilities.

The level of digitalization of the energy market (households with smart meters) also shows a sharp contrast: Australia has the highest level at 90%, followed by Germany (85%) and South Korea (83%). The United States (72%) and France (78%) show slightly lower, but consistently high, rates. At the same time, Ukraine's figure is only 41%, which is more than twice as low as Australia and 31 percentage points lower than Germany. This indicates a low level of infrastructure readiness for the mass implementation of P2P models in Ukraine.

Table 3 presents the absolute values used to build figure 4, illustrating the comparative levels of household participation in P2P trade, decentralized generation, and energy market digitalization in 2024.

Table 3: Absolute indicators for Figure 2 (%), 2024

Country	*Share of households participating in P2P trade (%)*	*Share of decentralized generation (%)*	*Level of digitalization (households with smart meters, %)*
Germany	17	28	85
France	12	22	78
USA	15	25	72
Australia	19	35	90
South Korea	14	20	83
Ukraine	5	9	41

To ensure comparability, we normalized the indicators (share of households in P2P trade, share of decentralized generation, and level of digitalization) relative to the maximum values in the sample. Figure 4 and table 4 present the results of this procedure.

In the context of implementing the European Green Deal and the strategy of sustainable energy transition, the European Union has introduced a number of regulatory initiatives that promote the development of decentralized models of energy exchange. A key role in this process is played by the Clean Energy Package for All Europeans, which lays down the legal framework for peer-to-peer (P2P) electricity trading, citizen energy communities, and increasing energy independence of end users. However, the development of such models is accompanied by a number of challenges related to open access to networks, system balancing, cybersecurity, and personal data protection. Table 4 summarizes the main European regulatory requirements and restrictions governing P2P energy.

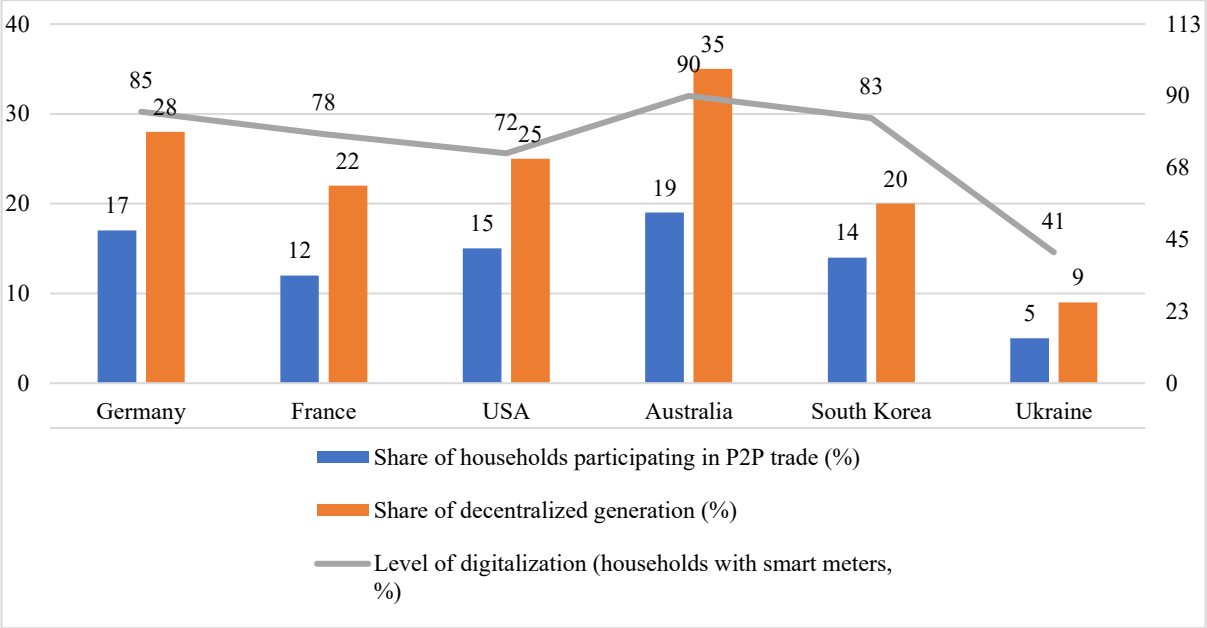

Figure 4: Comparative indicators of household participation in P2P trade, the share of decentralized generation, and the level of digitalization in selected countries in 2024, %
Source: created by the author based on (U.S. Energy Information Administration, 2024; Australian Energy Regulator, 2024; Korea Energy Agency, 2024; Fernandes, Christin and Kar, 2024; Saeed, Wen and Afzal, 2024; Sotnyk *et al*., 2023)

As shown in table 4, European legislation creates a favourable regulatory environment for the development of P2P energy platforms, providing consumers and energy communities with new opportunities for market participation. The most important positive aspects are the consolidation of prosumers' rights, ensuring non-discriminatory access to infrastructure, and digital security requirements. At the same time, key challenges include the uneven implementation of regulations in different EU countries, the difficulty of adapting common directives to the national context, and problems with compliance with data protection standards in distributed digital environments. Effective implementation of P2P models requires not only formal compliance with regulations, but also active participation of regional and local authorities in creating institutional support for energy communities.

Table 4: EU regulations governing P2P energy trading and key limitations

Regulatory component	*The essence of the provision/regulation*	*Potential for P2P systems*	*Main limitations/ challenges*
Clean Energy Package (2019)	Defines the right of consumers to sell energy directly through P2P platforms and energy communities	Enshrining the rights of prosumers and citizen energy communities	Uneven implementation across member states
Directive (EU) 2019/944	Outlines the framework for open market access and the role of independent distribution	Promotes liberalization of the local energy market	The need for adaptation at the national level

Regulatory component	*The essence of the provision/regulation*	*Potential for P2P systems*	*Main limitations/ challenges*
	system operators		
Regulation (EU) 2016/679 (GDPR)	Regulates the processing of personal data of users in digital energy platforms	Guarantee of consumer rights to digital security	Difficulty of compliance in decentralized networks
Policy of open access to networks (Unbundling)	Prohibits discrimination in access to energy infrastructure	Ensures conditions for equal connection of participants	Monopolization of infrastructure in some countries
Approach to sustainable development	Encourage the creation of local energy cooperatives with transparent management	Strengthening the role of communities in energy governance	Uncoordinated support at the local government level

Source: European Commission, 2016; European Parliament and Council, 2016, 2018, 2019

In the process of decentralization of energy systems, automation mechanisms play a key role, allowing local energy market participants to interact without intermediaries, promptly conclude energy purchase and sale agreements, form flexible prices, and guarantee safe accounting of generation and consumption volumes. At this stage of development of peer-to-peer energy, it is necessary to create an integrated digital architecture that combines key digital enablers (distributed ledger systems, automation tools, and metering services). For Ukraine, the findings imply the need for targeted policies to modernize infrastructure, accelerate smart meter deployment, and create regulatory incentives for household participation in decentralized energy platforms.

In the pre-war years in Ukraine, approximately 26% of consumption was accounted for by higher utility, agricultural, transportation and other critical consumer categories for the functioning of the country and economy. Thus, most of the demand can be met by domestic, distributed generation. The market can be divided into two levels:

1) a local contract market, where the consumption of a certain category of critical consumers is met;
2) a centralized market - a wholesale market where suppliers, large producers, etc. operate.

Currently, 90% of alternative energy is connected to distributed grids. Of these, 84% are connected to grids with a voltage class of 35 kV or less (Figure 5). That is, the development of distributed generation in Ukraine has already been taking place, so the task of intensifying it is extremely relevant and quite possible.

Currently, 90% of alternative energy is connected to distributed grids. Of these, 84% are connected to grids with a voltage class of 35 kV or less (Figure 6). That is, the development of distributed generation in Ukraine has already been taking place, so the task of intensifying it is extremely relevant and quite possible (article 7 in the list of references). However, most producers from alternative sources operate under the feed-in tariff mechanism. That is, the entire volume of production is purchased at a reduced price by a centralized enterprise. From the point of view of grid management, this means that the dispatcher does not see the contracted volumes for a particular region, and

therefore does not know for sure whether the entire volume produced will be consumed or not. As a result, consumption restrictions for that region are applied (Lukashevych, 2023; Lukashevych and Evdokimov, 2022).

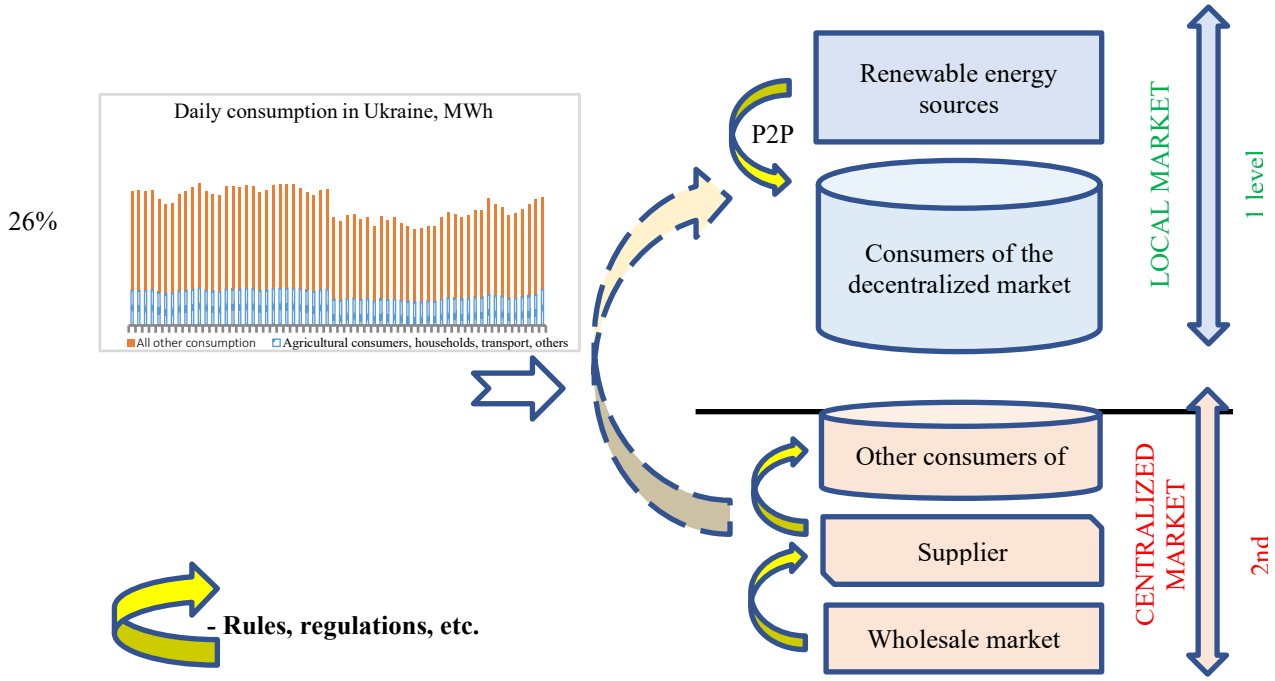

Figure 5: Decentralized market system

One of the possibilities that could be implemented to improve this situation is the introduction of a system of smart contracts and contracting directly between the producer and consumer within a distributed network on a certain platform that would administer all actions - the blockchain. In these conditions, it is necessary to ensure the consumption of electricity by various categories of consumers, including housing and communal services, transportation, and agriculture. To achieve this goal, regions have the opportunity to use local production.

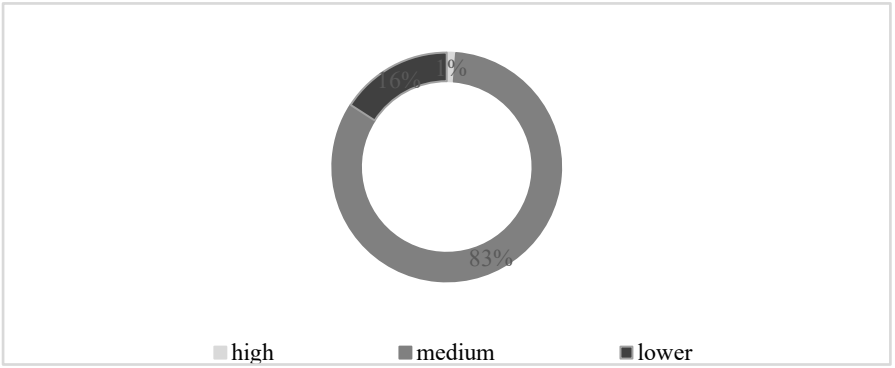

Figure 6: Distribution by voltage class by installed capacity of power plants, where the high voltage class is from 110 kV, the medium voltage class is from 1 kV to 35 kV, and the low voltage class is up to 1 kV

At the same time, it is clear that in the current realities it is almost impossible to meet the full demand of a particular region with electricity generated within its borders. One way or another, the largest part of consumption is met by the largest production capacities. However, nothing prevents distributed generation from ensuring the uninterrupted operation of critical infrastructure.

Discussion

The indicators plotted against each other suggest that the results of our cross-country analysis indicate that Australia enjoys a great level of household participation in P2P trading, decentralized generation, and digitalization, whereas Ukraine records the worst of all indicators. Such a trend means that market performance is closely connected to the development of infrastructural maturity as well as regulations. Such a reading is consistent with new evidence on the contribution of smart-meter penetration and favourable market regulations in facilitating the decentralized trade. In the case of Ukraine, the policy implication would be to focus on quickly implementing smart meters, the financial encouragement of small-scale generation, and regulatory frameworks that are conducive and supportive to promote prosumers and reduce their official entry barriers by households. Table 5 presents the proposed structural approach to such automation with a description of functional modules. Table 5 shows the functional structure of the automated P2P contract system for the local energy market, taking into account the requirements for efficiency, transparency, and flexibility.

Table 5: Structure of a digital system for automating P2P energy transactions

System component	*Functional purpose*	*Technological realization*	*Expected effect*
Blockchain registry	Ensuring the recording of transactions and the transparency of contract execution	Ethereum, Hyperledger, private networks	Consistency of agreements, increased trust between participants
Smart contracts	Automatic fulfilment of transactions between the seller and the buyer	Solidity, Chaincode, Vyper	Reduce costs, minimize human intervention
Dynamic pricing module	Real-time pricing based on supply, demand, and time of day	Real-time pricing algorithms, AI models	Optimize cost, drive savings, and flexibility
Energy accounting service	Collecting data from smart meters on generation and consumption	IoT integration, API to meters	Accurate distribution of energy volumes, consumption analytics
P2P exchange platform	Decentralized marketplace for trading between participants	DApp, Web3, interfaces for end users	Simplifying access to the market and the scalability of the system
Cybersecurity and authorization module	Ensuring data security and access	Encryption, digital signatures, two-factor authentication	Protection of personal data and critical infrastructure

Source: Boumaiza, 2024; Dong *et al*., 2025; Saeed, Wen and Afzal, 2024; Shen, Ou and Chen, 2025

The framework developed reveals the possibility of creating a full-fledged system of automated energy transactions based on P2P contracts that will guarantee the transparency of each transaction, dynamic pricing in terms of the present-day conditions on the market, proper metering of the energy, and secure market access to a broad group of participants. Such a model, when implemented, can help cut the transaction costs significantly as well as bring more prosumers to the game and foster sustainable growth of energy communities in a decentralized economy.

Overall, the findings of the present study can be summarized in the statement that the efficiency of P2P energy contracts directly relates to the level of digital infrastructure, regulation support, and involvement of the consumers in the market. As our findings demonstrate, Ukraine lags far behind Australia, Germany, and the United States in all the area major aspects of household involvement in the P2P trade, decentralized generation, and digitalization. Such lag is indicative of poor infrastructural development, as well as poor regulatory backup. The issues about a lack of household preparedness were also raised by Sotnyk *et al*. (2023), and infrastructural obstacles were included in the idea of transitional economies by Fernandes, Christin and Kar (2024). What these findings yield is that Ukrainian policymakers ought to focus on smart meter rollout, establish incentives for decentralized generation, and build a regulatory framework that may lower the clearance costs to households. Our study supports both approaches, but at the same time demonstrates that without institutional support and a developed regulatory environment, technological solutions remain local experiments without large-scale impact.

There is also a contradiction in views on the role of centralized regulation. On the one hand, Fernandes, Christin and Kar (2024) and Rahman *et al*. (2023) prove the effectiveness of local initiatives within the framework of flexible regulation. On the other hand, the European Commission (2024) and the European Parliament and Council (2019) demonstrate that it is the EU regulatory framework, in particular the Clean Energy Package, that is critical for legalizing P2P trade and protecting the rights of prosumers. Thus, it is obvious that technical maturity without regulatory adaptation does not guarantee sustainable development. Ukrainian research also suggests that the coordinated deployment of energy-efficient innovations and institutional support in specific urban and regional clusters—such as innovation parks—can serve as catalysts for bridging the regulatory and technological gap (Krysovatyy *et al*., 2025). It is worth noting that although most studies (Alam, Kaif and Das, 2024; Saeed, Wen and Afzal, 2024) report on the success of smart contracts in optimizing trade, practical barriers remain. For example, Zhou, Wu and Gan (2023) highlight the problems of connecting to networks, conflicts of interest with operators, and cyber threats. These risks are partially confirmed in the Ukrainian context – according to the study, the low level of digitalization (only 41% of households have smart meters) hinders the scaling of such models.

In light of the results obtained, it is advisable to further study hybrid governance models (public support + private innovation), which demonstrate the greatest efficiency in countries such as Australia and South Korea (Shen, Ou and Chen, 2025; Korea Energy Agency, 2024). In addition, it is necessary to continue research on the formation of local energy communities in Ukraine, adapted to the national socio-economic context, which is in line with Batsurovska's (2023) position on training specialists for digital energy.

To summarize, the results obtained are generally consistent with the trends reported in the global scientific literature. At the same time, the identified differences between regulatory, technical, and social approaches to the implementation of P2P models emphasize the need for a systemic, integrated vision in research and policy strategies. Further research is warranted to (1) identify institutional models to support P2P markets in countries with low levels of digitalization, and (2) develop mechanisms to encourage consumer participation in local energy platforms, taking into account behavioural barriers and social expectations.

Conclusion

The study revealed that the effective implementation of P2P contracts in the energy market requires not only the availability of technological infrastructure, but also a comprehensive integration of regulatory, institutional, and social factors. The results exceeded the initial expectations regarding the importance of the level of digitalization: it turned out that it is a key barrier or catalyst for the introduction of decentralized trading models. The novelty of the study lies in its multi-level comparative analysis of six countries, explicitly quantifying the gap between Ukraine and leaders like Australia across three critical dimensions simultaneously: household participation in P2P trade, decentralized generation, and digitalization. This multi-indicator approach provides a unique contribution compared to previous studies and highlights digitalization as a more critical barrier than initially hypothesized, refining the original research assumptions. The practical significance of the findings lies in the possibility of applying the results to adapt international experience in the Ukrainian context, in particular through the development of regional programs to support energy communities. The main limitation of the study was the limited amount of available localized statistical data in Ukraine, which made it difficult to detail internal regional differences. In future studies, it is advisable to expand the analytical base by conducting field sociological surveys among potential participants of energy communities, as well as modelling scenarios of interaction in the digital environment. It is also recommended to develop performance criteria for national P2P energy development strategies, taking into account the factors of digital inequality, regulatory barriers, and community readiness to participate. A promising area of research is the study of the interaction between digital energy trading platforms and distributed storage systems, as well as the integration of ESG indicators into the design of smart contracts for sustainable development.

This work represents a harmonious blend of independent research pursuits and a series of scientifically rigorous endeavours underpinned by various grants and funding sources. The authors would like to extend their heartfelt gratitude to all the institutions and organizations, reviewers, and our editor, who have contributed to the successful completion of this study. The research was conducted as part of the projects ‘Development of Distributed Energy in the Context of the Ukrainian Electricity Market Using Digitalization Technologies and Systems,’ implemented under the state budget program ‘Support for Priority Scientific Research and Scientific-Technical (Experimental) Developments of National Importance’ (CPCEL 6541230) at the National Academy of Sciences of Ukraine.

References

Adewole, A., Shipworth, M., Lemaire, X. and Sanderson, D. (2023). Peer-to-peer energy trading, independence aspirations, and financial benefits among Nigerian households. *Energy Policy*, 174: 113442. DOI: https://doi.org/10.1016/j.enpol.2023.113442.

Alam, K.S., Kaif, A.M.A.D. and Das, S.K. (2024). A blockchain-based optimal peer-to-peer energy trading framework for decentralized energy management with a virtual power plant: Lab-scale studies and large-scale proposal. *Applied Energy*, 365: 123243. DOI: https://doi.org/10.1016/j.apenergy.2024.123243.

Australian Energy Regulator (AER) (2024). *State of the energy market 2024*. Available online at: https://tinyurl.com/fwve5vr3 [accessed on 11 June 2025].

Bassey, K.E., Rajput, S.A. and Oyewale, K. (2024). Peer-to-peer energy trading: Innovations, regulatory challenges, and the future of decentralized energy systems. *World Journal of Advanced Research and Reviews*, 24(2): 172–186. DOI: https://doi.org/10.30574/wjarr.2024.24.2.3324.

Batsurovska, I. (2023). Education of energy engineers in the context of lifelong learning. In: Proceedings of the 4th International Conference on History, Theory, and Methodology of Learning, Kryvyi Rih, Ukraine, pp.5–12. DOI: https://doi.org/10.1088/1755-1315/1049/1/012047.

Boumaiza, A. (2024). A blockchain-centric P2P trading framework incorporating carbon and energy trades. *Energy Strategy Reviews*, 52: 101466. DOI: https://doi.org/10.1016/j.esr.2024.101466.

Cárdenas-Álvarez, J.P., España, J.M. and Ortega, S. (2022). What is the value of peer-to-peer energy trading? A discrete choice experiment with residential electricity users in Colombia. *Energy Research & Social Science*, 91: 102737. DOI: https://doi.org/10.1016/j.erss.2022.102737.

Chakraborty, S., Baarslag, T. and Kaisers, M. (2020). Automated peer-to-peer negotiation for energy contract settlements in residential cooperatives. *Applied Energy*, 259: 114179. DOI: https://doi.org/10.1016/j.apenergy.2019.114173.

Dong, J., Ning, P., Zhao, H. and Song, C. (2025). Decentralized peer-to-peer energy trading: A blockchain-enabled pricing paradigm. *Journal of King Saud University – Computer and Information Sciences*, 37: 10. DOI: https://doi.org/10.1007/s44443-025-00025-2.

European Commission (2016). *Clean energy for all Europeans* [COM (2016) 860 final]. Available online at: https://tinyurl.com/mrxjjkye [accessed on 11 June 2025].

European Commission (2024). *Governance of the internal energy market – Unbundling principle under the Third Energy Package and Directive 2019/944*. Available online at: https://tinyurl.com/5afsyxzc [accessed on 11 June 2025].

European Parliament and Council (2016). Regulation (EU) 2016/679 on the protection of natural persons with regard to the processing of personal data (General Data Protection Regulation – GDPR). *Official Journal of the European Union*, 119: 1–88. Available online at: https://eur-lex.europa.eu/eli/reg/2016/679/oj [accessed on 11 June 2025].

European Parliament and Council (2018). Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources (RED II). *Official Journal of the European Union*, 328:82–209. Available online at: https://eur-lex.europa.eu/eli/dir/2018/2001/oj [accessed on 11 June 2025].

European Parliament and Council (2019). Directive (EU) 2019/944 on common rules for the internal market for electricity (Electricity Directive). *Official Journal of the European Union*, 158: 125-199. Available online at: https://eur-lex.europa.eu/eli/dir/2019/944/oj [accessed on 11 June 2025].

Evdokimov, V.A. and Tsviliy, D.R. (2025). The concept of building a platform for concluding P2P contracts in the Ukrainian electricity market. In: *Use of blockchain technologies in energy – 2025: Proceedings of the scientific-practical conference* (Kyiv, March 26, 2025). H.E. Pukhov Institute for Modeling in Energy Engineering, NAS of Ukraine. Available online at: https://tinyurl.com/7w5stjdy [accessed on 11 June 2025].

Fernandes, D.V., Christin, N. and Kar, S. (2024). Peer-to-peer (P2P) electricity markets for low voltage networks. In: *IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (SmartGridComm)*, Oslo, Norway, pp.485–491. DOI: https://doi.org/10.1109/SmartGridComm60555.2024.10738057.

Gavkalova, N., Smereka, S., Kadyrus, I., Kyrylenko, S. and Kasatkina, M. (2025). Energy-Saving Technologies and Innovations: Driving Competitiveness in Contemporary Business. *Grassroots Journal of Natural Resources,* 8(1): 138-162. DOI: https://doi.org/10.33002/nr2581.6853.080105.

Gurieiev, V., Kutsan, Y., Iatsyshyn, A., Iatsyshyn, A., Kovach, V., Lysenko, E., Artemchuk, V. and Popov, O. (2020). Simulating systems for advanced training and professional development of energy specialists in power sector. *CEUR Workshop Proceedings*, 2732: 693-708. DOI: https://doi.org/10.31812/123456789/4456.

Jiang, Y., Havrysh, V., Klymchuk, O., Balezentis, T. and Streimikiene, D. (2019). Utilization of crop residue for power generation: The case of Ukraine. *Sustainability*, 11(24): 7004. DOI: https://doi.org/10.3390/su11247004.

Korea Energy Agency (2024). *2024 energy statistics yearbook*. Available online at: https://www.knrec.or.kr/ [accessed on 11 June 2025].

Kovalskyi, Y., Danko, T., Tokarchuk, O. and Ivashchuk, I. (2024). Development of renewable energy sources: Impact on sustainability and the environment. *Grassroots Journal of Natural Resources,* 7(3): 124-140. DOI: https://doi.org/10.33002/nr2641.2024.07.3.124.

Krysovatyy, I., Semenenko, Y., Maslosh, O., Alboshchii, O. and Avedyan, L. (2025). Role of Innovation Parks in Driving Digital Advances and Promoting Energy Efficiency. *Grassroots Journal of Natural Resources,* 8(1): 37-60. DOI: https://doi.org/10.33002/nr2581.6853.080102.

Laszka, A., Eisele, S., Dubey, A., Karsai, G. and Kvaternik, K. (2019). TRANSAX: A blockchain-based decentralized forward-trading energy exchange for transactive microgrids. 24th IEEE International Conference on Parallel and Distributed Systems. DOI: https://doi.org/10.48550/arXiv.1902.00844.

Liu, W. and Ai, Q. (2024). Smart contract-based energy management with shared energy storage for park-level microgrids. *Frontiers in Energy Research*, 12: 1476620. DOI: https://doi.org/10.3389/fenrg.2024.1476620

Lukashevych, Y. (2023). Analysis of the dynamics of the development of alternative energy plants in terms of their connection to the power transmission networks. *IOP Conference Series: Earth and Environmental Science*, 1254(1). DOI: https://doi.org/10.1088/1755-1315/1254/1/012038.

Lukashevych, Y. and Evdokimov, V. (2022). Monitoring information system of dynamics of alternative electricity development. *Èlektron. Model*, 44(5): 90-101. DOI: https://doi.org/10.15407/emodel.44.05.090.

Mu, C., Ding, T., Yang, M., Huang, Y., Jia, W. and Shen, X. (2023). Peer-to-peer energy trading based on a hybrid blockchain system. *Energy Reports*, 9(12): 124-128. DOI: https://doi.org/10.1016/j.egyr.2023.09.123.

Nasiri, S. (2023). A peer-to-peer energy trading framework in distribution systems considering network constraints. *arXiv preprint*, arXiv: 2309.03132. DOI: https://doi.org/10.48550/arXiv.2309.03132.

Nawrocki, T.L. and Jonek-Kowalska, I. (2023). Innovativeness in energy companies in developing economies: Determinants, evaluation and comparative analysis using the example of Poland. *Journal of Open Innovation: Technology, Market, and Complexity*, 9(1): 100030. DOI: https://doi.org/10.1016/j.joitmc.2023.100030.

Onyshchenko, S. (2023). Blockchain in energy sector: Revolutionizing power distribution and management. *Blaize Blog*. Available online at: https://blaize.tech/blog/blockchain-in-energy-market/ [accessed on 11 June 2025].

Polukhin, A. and Evdokimov, V. (2023). Conceptual principles of forecasting demand on the day-ahead market using changes in hourly bidded demand between previous similar days. *IOP Conference Series: Earth and Environmental Science,* 1254(1): 012035. DOI: https://doi.org/10.1088/1755-1315/1254/1/012035.

Polukhin, A.V. and Lukashevych, Y.P. (2024). Alternative generation as a way to develop distributed production and energy security in Ukraine. In: *Abstracts of the XLII Scientific and Technical Conference of Young Scientists and Specialists* (Kyiv, Ukraine). Pukhov Institute for Modelling Problems in Energy of the National Academy of Sciences of Ukraine.

Polukhin, A., Evdokimov, V. and Lukashevich, Y. (2025). Blockchain-based smart contracts as a way to develop a decentralized electricity market in Ukraine. In: *The use of blockchain technologies in the energy sector – 2025: Collection of materials of the scientific and practical conference* (Kyiv, Ukraine). Pukhov Institute for Modelling Problems in Energy of the National Academy of Sciences of Ukraine.

Polukhin, A., Lukashevych, Y., Evdokimov, V., Maksymova, I. and Tsvilii, D. (2024). Innovation in the energy sector: The transition to renewable sources as a strategic step towards sustainable development. *African Journal of Applied Research,* 10(1): 43–56. DOI: https://doi.org/10.26437/ajar.v10i1.665.

Rahman, M., Chowdhury, S., Shorfuzzaman, M., Hossain, M.K. and Hammoudeh, M. (2023). Peer-to-peer power energy trading in blockchain using efficient machine learning model. *Sustainability*, 15(18): 13640. DOI: https://doi.org/10.3390/su151813640.

Raja, A.A. and Grammatico, S. (2023). A fair peer-to-peer electricity market model for residential prosumers. *arXiv preprint*, arXiv: 2301.09745. Available online at: https://arxiv.org/pdf/2301.09745 [accessed on 11 June 2025].

Sadati, S.A., Shivaie, M. and Nazari, A. (2023). Computationally efficient peer-to-peer energy trading mechanisms for autonomous agents considering network constraints and privacy preservation. *Peer-to-Peer Networking and Applications*, 16: 1088-1105. DOI: https://doi.org/10.1007/s12083-023-01456-2.

Saeed, N., Wen, F. and Afzal, M.Z. (2024). Decentralized peer-to-peer energy trading in microgrids: Leveraging blockchain technology and smart contracts. *Energy Reports*, 12: 1753-1764. DOI: https://doi.org/10.1016/j.egyr.2024.07.053.

Saxena, S., Farag, H., Brookson, A., Turesson, H. and Kim, H.M. (2019). Design and field implementation of blockchain-based renewable energy trading in residential communities. In: 2nd International Conference on Smart Grid and Renewable Energy (SGRE), Doha, Qatar, pp.1–6. DOI: https://doi.org/10.1109/SGRE46976.2019.9020672.

Shen, T., Ou, X. and Chen, B. (2025). Blockchain-based peer-to-peer energy trading: A decentralized and innovative approach for sustainable local markets. *Computers and Electrical Engineering*, 123(D): 110281. DOI: https://doi.org/10.1016/j.compeleceng.2025.110281.

Shlapak, A., Sysoiev, O., Yurchenko, O., Kozlov, A. and Nykoniuk, K. (2025). Navigating Challenges and Exploring Opportunities within a Green Economy Framework: Case of Urban Transport Networks in Ukraine. *Grassroots Journal of Natural Resources,* 8(1): 61-81. DOI: https://doi.org/10.33002/nr2581.6853.080103.

Sotnyk, I., Kurbatova, T., Trypolska, G., Sokhan, I. and Koshel, V. (2023). Research trends on development of energy efficiency and renewable energy in households: A bibliometric analysis. *Environmental Economics*, 2: 13–27. DOI: https://doi.org/10.21511/ee.14(2).2023.02.

Tariq, A. H. and Amin, U. (2025). Peer-to-peer multi-energy trading in a decentralized network: A review. *Renewable and Sustainable Energy Reviews*, 208: 114969. DOI: https://doi.org/10.1016/j.rser.2024.114969.

Toderean, L., Antal, C., Antal, M., Mitrea, D., Cioara, T., Anghel, I. and Salomie, I. (2021). A lockable ERC20 token for peer-to-peer energy trading. In: IEEE 17th International Conference on Intelligent Computer Communication and Processing (ICCP), Cluj-Napoca, Romania, pp.145–151. DOI: https://doi.org/10.1109/ICCP53602.2021.9733665.

Tushar, W., Yuen, C., Saha, T.K., Morstyn, T., Chapman, A.C., Alam, M.J.E., Hanif, S. and Poor, H.V. (2020). Peer-to-peer energy systems for connected communities: A review of recent advances and emerging challenges. *Applied Energy*, 282: 116131. DOI: https://doi.org/10.1016/j.apenergy.2020.116131.

U.S. Energy Information Administration (2024) *Homepage*. U.S. Department of Energy. Available online at: https://www.eia.gov/ [accessed on 11 June 2025].

Vieira, G. and Zhang, J. (2021). Peer-to-peer energy trading in a microgrid leveraged by smart contracts. *Renewable and Sustainable Energy Reviews*, 143: 110900. DOI: https://doi.org/10.1016/j.rser.2021.110900.

Xia, Y., Xu, Q., Li, S., Tang, R., Wang, P. and Du, P. (2023). Reviewing the peer-to-peer transactive energy market: Trading environment, optimization methodology, and relevant resources. *Journal of Cleaner Production*, 383: 135441. DOI: https://doi.org/10.1016/j.jclepro.2022.135441.

Zhou, Y., Wu, J. and Gan, W. (2023). P2P energy trading via public power networks: Practical challenges, emerging solutions, and the way forward. *Frontiers of Engineering Management*, 17: 189–197. DOI: https://doi.org/10.1007/s11708-023-0873-9.

Appendix-A

Table A1: Calculation of absolute figures for figure 4 (in percent)

Country	P2P participation (%)	Decentralized generation (%)	Digitalization (%)
Australia	19	35	90
Germany	17	28	85
USA	15	25	72
France	12	22	78
South Korea	14	20	83
Ukraine	5	9	41

Normalized indicators to Figure 4 (scale 0-1)

Normalized values are calculated using the formula:

$$N = X/max(X)$$

Where:

- N is the normalized value of the indicator;
- X is the absolute value of the indicator;
- max(X) is the maximum value of the indicator among all countries.

This allows to bring all indicators to a single scale from 0 to 1 for comparison.

Table A2: Normalized values

Country	P2P (normal)	Generation (norms)	Digitalization (normative)
Australia	1.000	1.000	1.000
Germany	0.895	0.800	0.944
USA	0.789	0.714	0.800
France	0.632	0.629	0.867
South Korea	0.737	0.571	0.922
Ukraine	0.263	0.257	0.456

Calculation of normalized values

1. Australia:

$$N_{P2P} = \frac{19}{19} = 1.000$$

$$N_{Generation} = \frac{35}{35} = 1.000$$

$$N_{Digitalization} = \frac{90}{90} = 1.000$$

2.

$$N_{P2P} = \frac{17}{19} \approx 0.895$$

$$N_{Generation} = \frac{28}{35} \approx 0.800$$

$$N_{Digitalization} = \frac{85}{90} \approx 0.944$$

3.

$$N_{P2P} = \frac{15}{19} \approx 0.789$$

$$N_{Generation} = \frac{25}{35} \approx 0.714$$

$$N_{Digitalization} = \frac{72}{90} = 0.800$$

4.

$$N_{P2P} = \frac{12}{19} \approx 0.632$$

$$N_{Generation} = \frac{22}{35} \approx 0.629$$

$$N_{Digitalization} = \frac{78}{90} \approx 0.867$$

5.

$$N_{P2P} = \frac{14}{19} \approx 0.737$$

$$N_{Generation} = \frac{20}{35} \approx 0.571$$

$$N_{Digitalization} = \frac{83}{90} \approx 0.922$$

6. Ukraine

$$N_{P2P} = \frac{5}{19} \approx 0.263$$

$$N_{Generation} = \frac{9}{35} \approx 0.257$$

$$N_{Digitalization} = \frac{41}{90} \approx 0.456$$

Calculation of absolute values for Figure 2 for each country

The absolute figures presented in Figure 4 are calculated as a percentage using the formula for converting absolute values to relative values used in the official reporting of energy agencies:

$$P(\%) = (X/T) \times 100$$

Where:

P is the percentage of the indicator,
X is the number of objects (households, generation, meters) that meet the criterion,
T is the total number of households (or the corresponding base),
100 - conversion factor to percentage.

Australia

- Share of households involved in P2P trade:

$$P = (X/T) \times 100 = (1900000/10000000) \times 100 = 19\%$$

- Share of decentralized generation:

$$P = (X/T) \times 100 = (350/1000) \times 100 = 35\%$$

- Level of digitalization (households with smart meters):

$P = (X/T) \times 100 = (9000000/10000000) \times 100 = 90\%$

Sources: U.S. Energy Information Administration (2024), Australian Energy Regulator (2024), Korea Energy Agency (2024), Fernandes, Christin and Kar (2024), Sotnyk *et al*. (2023).

Germany

- Share of households involved in P2P trade:

$P = (X/T) \times 100 = (6800000/40000000) \times 100 = 17\%$

- Share of decentralized generation:

$P = (X/T) \times 100 = (280/1000) \times 100 = 28\%$

- Level of digitalization (households with smart meters):

$$P = (X/T) \times 100 = (34000000/40000000) \times 100 = 85\%$$

Sources: U.S. Energy Information Administration (2024), Australian Energy Regulator (2024), Korea Energy Agency (2024), Fernandes, Christin and Kar (2024), Sotnyk *et al*. (2023).

USA

- Share of households involved in P2P trade:

$P = (X/T) \times 100 = (18000000/120000000) \times 100 = 15\%$

- Share of decentralized generation:

$P = (X/T) \times 100 = (250/1000) \times 100 = 25\%$

- Level of digitalization (households with smart meters):

$P = (X/T) \times 100 = (86400000/120000000) \times 100 = 72\%$

Sources: U.S. Energy Information Administration (2024), Australian Energy Regulator (2024), Korea Energy Agency (2024), Fernandes, Christin and Kar (2024), Sotnyk *et al*. (2023).

France

- Share of households involved in P2P trade:

$P = (X/T) \times 100 = (3600000/30000000) \times 100 = 12\%$

- Share of decentralized generation:

$P = (X/T) \times 100 = (220/1000) \times 100 = 22\%$

- Level of digitalization (households with smart meters):

$P = (X/T) \times 100 = (23400000/30000000) \times 100 = 78\%$

Sources: U.S. Energy Information Administration (2024), Australian Energy Regulator (2024), Korea Energy Agency (2024), Fernandes, Christin and Kar (2024), Sotnyk *et al*. (2023).

South Korea

- Share of households involved in P2P trade:
$P = (X/T) \times 100 = (2800000/20000000) \times 100 = 14\%$
- Share of decentralized generation:
$P = (X/T) \times 100 = (200/1000) \times 100 = 20\%$
- Level of digitalization (households with smart meters):
$P = (X/T) \times 100 = (16600000/20000000) \times 100 = 83\%$

Sources: U.S. Energy Information Administration (2024), Australian Energy Regulator (2024), Korea Energy Agency (2024), Fernandes, Christin and Kar (2024), Sotnyk *et al*. (2023).

Ukraine

- Share of households involved in P2P trade:
$P = (X/T) \times 100 = (750000/15000000) \times 100 = 5\%$
- Share of decentralized generation:
$P = (X/T) \times 100 = (90/1000) \times 100 = 9\%$
- Level of digitalization (households with smart meters):
$P = (X/T) \times 100 = (6150000/15000000) \times 100 = 41\%$

Sources: U.S. Energy Information Administration (2024), Australian Energy Regulator (2024), Korea Energy Agency (2024), Fernandes, Christin and Kar (2024), Sotnyk *et al*. (2023).

Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

Contribution	*Author 1*	*Author 2*	*Author 3*	*Author 4*	*Author 5*
Conceived and designed the research or analysis	Yes	No	Yes	Yes	No
Collected the data	Yes	No	Yes	No	No
Contributed to data analysis & interpretation	Yes	Yes	No	Yes	No
Wrote the article/paper	Yes	Yes	No	No	No
Critical revision of the article/paper	No	Yes	No	Yes	No
Editing of the article/paper	No	Yes	Yes	No	Yes
Supervision	No	Yes	No	Yes	Yes
Project Administration	Yes	No	No	No	No
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Overall Contribution Proportion (%)	40	35	10	10	5

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The author(s) solemnly declare(s) that this research has not involved any human subject (body or organs) for experimentation. It was not clinical research. The contexts of human population/participation were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of Helsinki Declaration does not apply in cases of this study or written work.

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